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EFFECTS OF ATTACHMENT THICKNESS AND WELD PROFILE ON FATIGUE LIFE OF WELDED JOINTS

O. VOSIKOVSKY, R. BOUCHARD and A. RIVARD
ENGINEERING PHYSICS SECTION

AUGUST, 1988

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REPORT: MTL 88-4(TR)

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ABSTRACT

Results from an exploratory experimental program on evaluation of effects of smaller attachment thickness and improved weld profile (concave shape achieved by welding as per AWS D 1.1-86 Code) on fatigue life of load-carrying welded joints with transverse welds are reported.

The reduced attachment thickness and the concave weld profile provide significant improvements only in long lives. For 52 mm thick plate welded T-joints the reduction in attachment thickness by one half increased fatigue life at stress range of 100 MPa by 50-80%. The improved weld profile on joints with 26 mm thick attachments doubled the fatigue life.

LABORATOIRES DE LA TECHNOLOGIE DES MÉTAUX
RAPPORT: MTL 88-4 (J)

EFFETS DE L'ÉPAISSEUR DE L'ÂME ET DU PROFIL DU CORDON DE SOUDURE SUR LA DURÉE DE VIE EN FATIGUE DE JOINTS SOUDÉS.

par

O. Vosikovsky, R. Bouchard et A. Rivard

RÉSUMÉ

Le rapport porte sur les résultats d'un programme expérimental d'évaluation des effets de l' épaisseur d'âme plus minces et de profils de cordon de soudure améliorés (profils concaves obtenus par soudage conformément à la norme AWS D1.1-86) sur la durée de vie en fatigue de joints soudés transversalement.

La réduction de l'épaisseur de l'âme et le profil concave de la soudure n'améliorent significativement que les longues durées de vie en fatigue. Pour une plaque de 52 mm d'épaisseur de l'âme augmentera la duré de vie en fatigue de 50 à 80% pour un niveau de contrainte de 100 MPa. Le pofil amélioré de la soudure sur un joint de plaques de 26 mm doublera sa durée de vie.

INTRODUCTION

The adverse effect of increasing section thickness on fatigue life of welded joints, extensively researched during last ten years, has been recently reviewed by Berge and Webster [1]. The review concludes that joints with transverse welds of a variety of designs and weld profiles show about the same adverse thickness effect. The only exceptions are non-load-carrying joints with an attachment plate much thinner than the base plate. For these joints the thickness effect (derived from variation in base plate thickness only) appears to be weaker.

The thickness effect derived from tests of joints with equal base and attachment plate thicknesses was incorporated into European design and construction standards for offshore structures in 1984 [2,3]. At present it is being adopted in the Canadian offshore standard [4].

The American offshore standards do not reduce design fatigue life for joints with increased section thickness [5]. Instead, the 1986 AWS D 1.1 Code is based on an approach developed by Marshall [6], using an improvement in weld profiles to mitigate the adverse effect of increasing thickness.

Recent experimental results from non-load-carrying welded joints indicate that the thickness effect is much less severe when the attachment thickness is less than half that of the base plate [1,7,8]. Since the majority of welded joints in offshore structures have attachments much thinner than main members, their design using life reductions derived from tests of fully scaled up joints may be excessively conservative. These results also suggest that AWS D1.1 requirements for compensation of adverse thickness effect by improvement of weld profiles, based on attachment thickness only, may be warranted. However, for correct adjustment of the thickness effect, two parameters have to be used to allow for differences in base and attachment plate thicknesses. Maddox [8] proposed the base member thickness and the distance between weld toes of attachment welds, equal to attachment thickness plus two weld leg lengths, as the most relevant parameters.

The available evidence on the ability of improved weld profiles as per AWS D 1.1 Code to fully compensate the adverse effect of increasing thickness appears to be insufficient. The justification of the Code requirements [6] is based on fracture mechanics analysis and a few inconclusive test results [9].

The UKOSRP II welded plate joint test series, conducted in air, and seawater under optimum cathodic protection [10], showed only marginal improvement in long fatigue life in air achieved by the concave weld profile. The lives in seawater for joints with straight and concave weld profiles were similar. Bignonnet [11] found significant improvement in lives measured both in air and seawater for joints with concave welds deposited by using special techniques and electrodes. However, the plate joints used hadan attachment thickness equal to half of the base plate thickness, and the fatigue lives are compared with reference data from joints with equal

attachment and base plate thicknesses. Thus, the thinner attachment plate in joints with profiled welds may have contributed to life improvement. Haagensen et al [12] reported 27% gain in fatigue strength at 2 x 10^6 cycles for plate joints with the AWS concave weld profile. This increase is equivalent to the increase in strength allowed by the AWS Code for profiled welds.

The majority of the reviewed data show that the thickness effect can be significantly relaxed in welded joints with thin attachments, and that weld profiling may be a feasible way to mitigate the thickness effect. However, all sets of data, with the exception of one [11], were measured on joints with non-load-carrying welds. In order to extend the benefits to load-carrying joints, and in particular to tubular joints, data from tests of load-carrying joints are required. For quantification of the effects and their incorporation into Codes, a much more extensive data base is needed, particularly for thick joints where reduction in the thickness effect is most urgent.

To see whether benefits from reduced attachment thickness and improved weld profile would be sufficient to justify a major research program aimed at quantification of these benefits, a small exploratory test series designed to estimate the potential life improvements has been completed. Two sets of heavy-plate T-joints with load-carrying welds and attachment thickness equal to half of that of the base plate were tested. The first set had regular 45° welds, the second set had welds with an AWS improved weld profile. The results, compared with data from the recently completed Canadian research program on thickness effect in fully scaled up joints with 45° straight welds [9,13-16], are presented in this report.

TEST JOINTS AND MATERIAL

The geometry, loading, and dimensions of tested plate T-joints are shown in Fig. 1. The joints with equal base and attachment plate thicknesses T = t = 52 mm were tested in the first phase of the research program, evaluating the thickness effect [13-16]. The joints with thinner attachments t = 26 mm with either straight 45° or AWS concave welds were fabricated from plates, manufactured to Lloyd`s LT60 specification for normalized Grade 350, used in the first phase. The chemical composition and mechanical properties of these plates are given in Table 1.

The attachments were welded by full penetration manual welds in the vertical-up (3G) position. E7018 electrodes of 3.2 and 4.0 mm diam and average heat input of 1.4 kJ/mm were used. Preheat temperature was 70°C. The joints were welded without any restraint and tested in the as-welded condition. The weld toe pass on the base plate was deposited before the capping passes, and it had to satisfy the "dime" test, on 45° welds with the "dime" diam specified in Fig. 2a, to ensure favorable geometry of the weld toe.

The welds with improved, concave, profiles were deposited as per AWS D 1.1 [5] recommendations shown in Fig. 2a. Only the overall, and the base-plate weld-toe profiles (where fatigue cracks started) were controlled. To achieve the ideal profile over the whole weld length the welds were superficially ground. During the grinding only the tops of weld beads were removed.

The area near the weld toe was left as welded. Examples of welds with 45° and AWS profiles are shown in etched cross-sections made from fractured specimens in Fig. 2(b,c).

The geometry of the weld toe, defined by weld toe radius r, and by weld toe angle θ, was measured on sectioned RTV rubber casts of weld profiles. At least eight measurements were made on each test joint on sections spaced about 20 mm apart. Photographs of the cross sections magnified five times were used for measurements. The results for each tested joint, in terms of minimum, maximum, mean r and θ, and standard deviations S_r and S_θ, are presented in Table 2. The joints are identified by base over attachment plate thickness T/t, test stress range $\Delta\sigma$, and overall weld shape (45° or AWS).

EXPERIMENTAL PROCEDURES

The T-joints were tested in 3-point bending, with loads applied through the attachment, as shown in Fig. 1. Special frames, with adjustable-position reaction beams, were designed to achieve proper alignment of the joints. The alignment was checked by two strain gauges attached at mid-width of the base plate, 30 mm from the weld toes. Strain measurements were made at incrementally increased loads after application of about 200 cycles of test fatigue loads.

Fatigue tests were conducted at constant amplitude loading with a load ratio R = 0.05, at frequencies of 3 to 10 Hz. During the tests, fatigue crack growth and actuator displacement range were monitored.

For crack depth and shape measurements, a combination of AC potential drop (ACPD) technique and beach marking was used. Eighteen active ACPD probes with distance and spacing of 10 mm, as shown in Fig. 1, were spot welded along the weld toe. Two reference probes were located one quarter width distance from joint edges were used. The AC potential was measured with a Unit Inspection Crack Micro-Gauge linked to a computer.

For all welded joints, only one weld toe was instrumented. The other weld toe on the opposite side of the attachment plate was ground to ensure that fatigue cracks started to grow from the instrumented weld toe.

Five beachmarks were produced on each joint. The first one was made by ink staining when the deepest crack reached 2-4 mm. It indicated the number and shape of initiated cracks. Subsequent beachmarks were made by reducing the load range by 50% and doubling the frequency for an appropriate number of cycles to produce an ≈0.1 mm crack extension. The crack depths measured from beachmarks on fractured specimens were used for calibration of the ACPD measurements. The accuracy of the crack depth measurements is estimated at ±0.5 mm. More details on the ACPD technique and its calibration are given in [9,13,16,17].

EXPERIMENTAL RESULTS

The measured fatigue lives of welded joints with three geometries, tested at four stress ranges, are presented in Table 3. The total life (endurance) is defined by the number of cycles N_t at which the maximum crack depth reaches half of the base plate thickness. The crack initiation life is defined by the number of cycles N_i at which the deepest initiated crack depth reaches 0.5 mm. This definition of initiation life was chosen for convenience. A crack of 0.5 mm depth is the smallest one that could be sized with confidence by the potential drop techniques used, and is near the upper bound for short cracks [9,13-17]. The fatigue crack propagation life $N_p = N_t - N_i$.

The effects of reduced attachment thickness and improved weld profile on total, initiation, and propagation lives are shown in terms of S-N curves in Fig. 3(a-c). For joints with T = t = 52 mm, additional results from five tests, conducted at the University of Waterloo within the joint program on evaluation of the thickness effect, are included [14]. Since the U. of Waterloo tests produced slightly longer lives than those measured during MTL tests, two lines were fitted to the data for comparison with the other joint geometries, one to the combined data set, the other to the MTL data only.

The stress ranges used in the plots are the calculated nominal stress ranges at the weld toes. As can be seen from Table 3, the stress ranges extrapolated from strain gauge measurements are on average about 4% lower. The difference appears to increase with decreased attachment thickness. A similar trend was observed in the previous test program [16].

The effect of thinner attachment and of improved weld profile on fatigue crack growth in a particular stress range is shown in Fig. 4(a-d). The crack depths in these curves are the ACPD measurements from the probe nearest to the deepest initial crack. The crack initiation and total lives for a = 0.5 mm and T/2 were determined from these plots. As can be observed here or in Fig. 3, both initiation and propagation lives increase when attachment thickness is reduced and/or weld profile is improved, in particular at lower stress ranges.

The beachmarks, in addition to providing means for accurate calibration of the ACPD measurements, supplied information on multiple crack initiation and coalescence. The number of initiated cracks in the tested joints, counted from indications of the first (ink-stain) beachmark, are given in Table 4. An example of change in crack shape development with change in attachment thickness and weld profile is shown in Fig. 5, where fractures of three joints with different geometries tested at 150 MPa stress range are shown. The pattern in crack development for joints with 45° welds is similar, Fig. 5(a,b). However, in the joint with concave weld, the fatigue cracks over almost half the length of the weld, as marked by arrows in Fig. 5(c), initiated between the toe pass and the first capping pass. These cracks initiated outside the ACPD probes. The large size of one crack in Fig. 5(c) shows that it initiated well in advance of the weld toe cracks. The estimated initiation life for this crack is given in Table 3.

Two other joints, one with 45° weld, exhibited crack initiation between toe and capping passes. In these joints, listed in Table 4 with the number of between-pass cracks in parentheses, the weld toe cracks initiated earlier or at the same time. Since the weld toe and the between-pass cracks started to grow in planes close to 5 mm apart (distance between the weld toe and the toe of the first capping pass), they did not completely coalesce until the crack depth reached half of the plate thickness,i.e., end of the test. Thus for joints with between-pass initiated cracks, major cracks remained semi-elliptical with high aspect ratio in shape through useful fatigue life.

DISCUSSION

The results obtained from this exploratory experimental program clearly indicate that the adverse effect of increasing thickness is reduced when the attachment plate is thinner than the base plate, even for load-carrying transverse welded joints. Further improvement in fatigue life can be achieved by using AWS concave profile welds instead of common straight profile welds.

The fitted S-N curves in Fig. 3 show that significant improvements are obtained only at low stress ranges (long life). The extrapolated curves for total and propagation lives intersect at about 300 MPa, indicating negligible effects at high stress ranges (short life). This is in agreement with the UKOSRP experiments [10] and results reported by Noordhoek et al [7]. The improvements, at low stress range (100 MPa) are presented in Table 5, as ratios of lives determined from S-N curves for the three joint geometries. N_B/N_A is the life extension from halving the attachment thickness, N_C/N_B is the life extension from improving weld profile, and N_C/N_A is the combined life extension.

As can be seen from Table 5, halving the attachment thickness increases total life by 50-80%. Improving the weld profile doubles the total fatigue life. This is less than the credit given for weld profiling by AWS Code [5]. The X_1 S-N curve used in design of joints with attachment thickness up to 25 mm and improved weld profiles, allows 2.8x longer life than the X_2 curve for joints with non-improved welds, at $\Delta\sigma$ = 100 MPa. However, it should be noted that the test of the joint with AWS profile at 100 MPa was a run out. This means that weld profiling may increase the fatigue limit above 100 MPa. Because of inherent scatter in life of welded joints, a much more extensive test program would be required to establish this with confidence. The design life for offshore structures is over 10^8 cycles, and thus any increase in fatigue limit is very important.

Comparison of the attachment thickness and weld shape effects on total, initiation, and propagation lives (Fig. 3, Table 5) shows that initiation life is the most affected. This can be expected since crack initiation is primarily determined by the local stress concentration factor which is expected to decrease with thinner attachments and weld profiling [6].

No correlation is observed between initiation life and local weld-toe geometry,defined by weld toe angle θ and weld-toe radius r in Table 2. Except for the mean value of r, which was close to 1 mm for all joints, the data are widely scattered. From the scatter it may be inferred that in each joint there were many locations along the weld toe with critical combinations of high angle and sharp radius where fatigue cracks initiated. Table 4 shows that the number of initiated cracks generally declined with decreasing weld-toe stress peak, i.e., decreasing stress range and stress concentration factor. Variation in the density of potential crack initiation sites in the joints tested may be responsible for fluctuations in the numbers of initiated cracks.

The fatigue crack propagation lives are less affected by variation in attachment thickness and weld profile. The improvement in propagation life is obtained from two sources. (i) As shown in Table 4, a smaller number of weld-toe cracks initiate in specimens with thinner attachments and profiled welds. This results in delayed coalescence of multiple cracks into a single nearly-straight-fronted crack. Since semi-elliptical cracks grow slower than a straight-fronted crack of the same depth, the propagation life is extended [9,13]. (ii) The local weld-toe stress peak drops to nominal stress values within a distance equal to about 10% of the plate thickness [18]. Thus growth of only shallow cracks, up to ≈5 mm deep, can be affected by variation in the local stress concentration. Indications that shallow fatigue cracks grow faster in 52/52-45° joints than in 52/26-45° and 52/26-AWS joints can be seen in Fig. 6(a-c), where fatigue crack growth rates da/dN, are plotted vs crack depth a, at stress ranges of 100, 150, and 200 MPa. The growth rates were calculated using the incremental polynomial method [19] from data presented in Fig. 4.

One curve for each stress range shows a considerable dip in growth rate at intermediate crack depths. These curves pertain to joints where some cracks initiated between weld toe and capping passes. The weld-toe cracks cannot coalesce with cracks initiated between passes and thus grow as high-aspect-ratio semi-elliptical cracks, Fig. 5(c). Lower stress intensity factors associated with such cracks [15,18] result in lower growth rates. When all cracks initiate at the weld toe, their coalescence is completed early, and the remaining life associated with propagation of a nearly-straight-fronted crack is shorter [9].

The gain in crack propagation life from this process is relatively small. The main expected benefit from weld improvement techniques is the extended initiation life. If only the near-weld-toe geometry is improved, e.g., by weld-shape profiling, using special electrodes for the weld-toe pass, weld-toe grinding, peening, TIG or plasma dressing, the cracks can initiate between capping passes and thus wipe out much of the benefit from the improved weld toe.

CONCLUSIONS

The following conclusions, based on limited literature review and the present small exploratory experimental program, can be made on the benefits of smaller attachment thickness and weld profiling in fatigue life of welded joints.

a) Reducing attachment thickness generates significantly improved fatigue life of transverse load-carrying welded joints, but only at long lives. Halving the attachment thickness in 52 mm thick joints resulted in 50-80% increase in fatigue life at a stress range of 100 MPa.

b) Similarly, improving weld profile as per AWS D1.1-86 Code extends fatigue life at low stress. Improving the weld profile resulted in doubling the fatigue life compared to 45° straight welds at a stress range of 100 MPa. The life improvement may be accompanied by a significant increase in fatigue limit.

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Table 1 - Mechanical properties and chemical composition of the 52-mm thick plate

Yield strength (MPa)				UTS (MPa)				Elongation (%)			
390				517				32			
C	Mn	Si	S	P	Al	Ni	Cr	Mo	Cu	V	Nb
0.12	1.39	0.28	0.011	0.017	0.027	0.15	0.17	≤0.01	0.15	0.053	0.041

Table 2 - Measured weld leg lengths, l, minima, maxima, means and standard deviation, S, of base plate weld-toe angles θ and radii r for tested joints

Specimen T/t-Δσ-weld	ℓ (mm)	θ_{min} (deg)	θ_{max} (deg)	θ_{mean} (deg)	S_θ (deg)	r_{min} (mm)	r_{max} (mm)	r_{mean} (mm)	S_r (mm)
52/52-100-45°	32	33	57	39	8	0.5	3.3	1.3	1.1
52/52-150-45°	32	33	55	41	7	0.5	1.8	1.1	0.5
52/52-200-45°	29	33	45	39	4	0.2	3.0	1.1	1.0
52/26-100-45°	16	22	35	29	4	0.2	3.0	1.3	0.9
52/26-120-45°	15	29	63	36	11	0.2	3.0	0.8	0.9
52/26-150-45°	14	32	69	52	15	0.3	3.0	1.9	0.9
52/26-200-45°	14	27	58	35	11	0.3	1.6	0.7	0.5
52/26-100-AWS	17	33	53	44	6	0.2	2.8	0.9	0.8
52/26-120-AWS	17	27	53	39	10	0.5	1.4	0.9	0.4
52/26-150-AWS	15	22	41	33	7	0.2	2.7	0.9	0.8
52/26-200-AWS	15	30	42	36	4	0.1	1.4	0.6	0.5

Table 3 - Endurance and crack initiation life of welded joints

Joint T/t-Δσ-weld	Stress range (MPa) Calculated (MPa)	Stress range (MPa) Measured* (MPa)	Endurance N_t $a_f = T/2$ (k cycles)	Crack initiation life N_i $a_i = 0.5$ mm (k cycles)	Crack initiation life N_i $a_i = 0.5$ mm % endurance
52/52-100-45°	100	99.3	1210	380	31.4
52/52-150-45°	150	145.5	370	90	24.3
52/52-200-45°	200	197.7	137	37	27.0
52/26-100-45°	100	95.5	2440	920	37.7
52/26-120-45°	120	115.0	1158	380	32.8
52/26-150-45°	150	145.0	539	150	27.8
52/26-200-45°	200	192.2	196	62	31.6
52/26-100-AWS	100	93.1	--	>8000	--
52/26-120-AWS	120	113.5	1966	670	34.0
52/26-150-AWS	150	144.0	940	470**	50.0
52/26-200-AWS	200	195.0	238	65	27.4

* Extrapolated from strain gauge measurements.

** First crack initiated in between the weld toe and 1st capping passes at ~340 k cycles.

Table 4 - Number of initiated cracks in tested joints

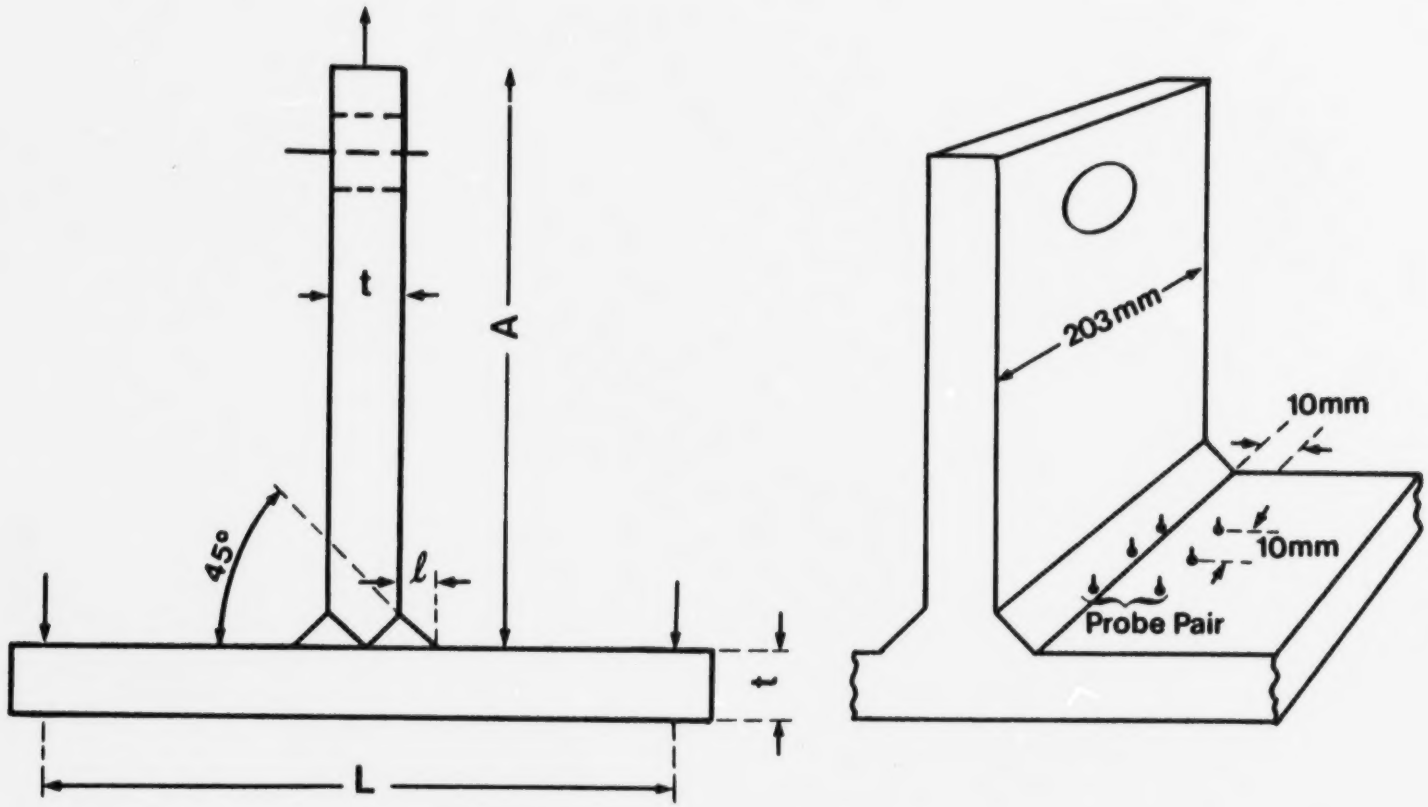
Specimen T/t-weld	Stress range (MPa) 100	120	150	200
52/52-45°	12	--	20	37
52/52-45°	8 (2)*	21	19	32
52/26-AWS	--	5	5 (5)*	28 (6)*

* Numbers in brackets are number of cracks initiated between the weld toe and the first capping passes.

Table 5 - Life extension ratios $\Delta\sigma$ = 100 MPa

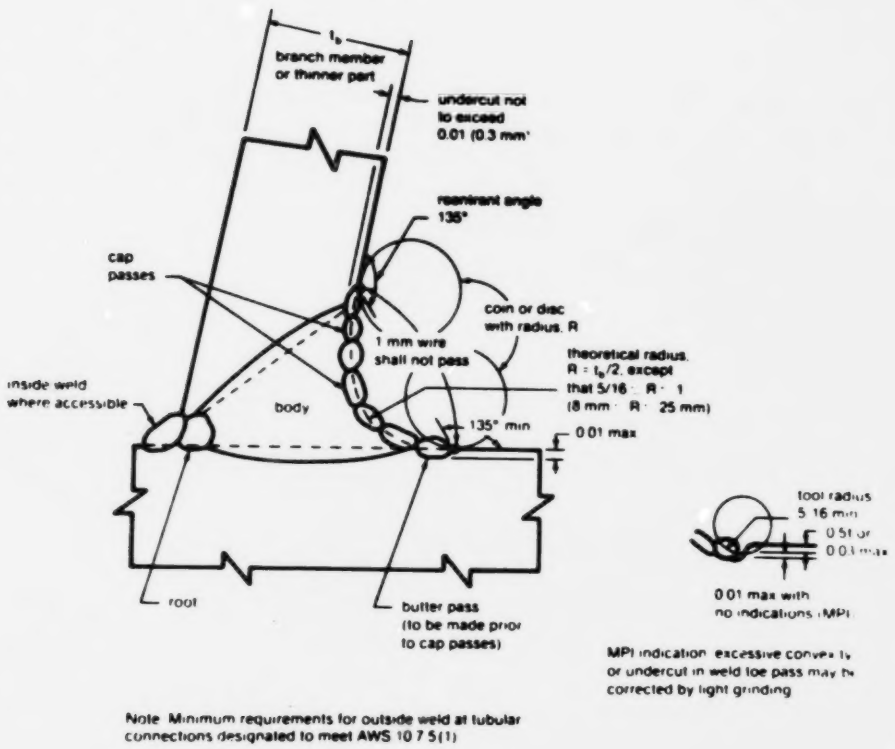
	N_B/N_A	N_C/N_B	N_C/N_A
Total life	1.5 (1.8)	2.0	3.0 (3.5)
Initiation life	2.0 (2.3)	2.3	4.7 (5.4)
Propagation life	1.4 (1.7)	1.7	2.3 (2.8)

Values in brackets use N_A from MTL data only.

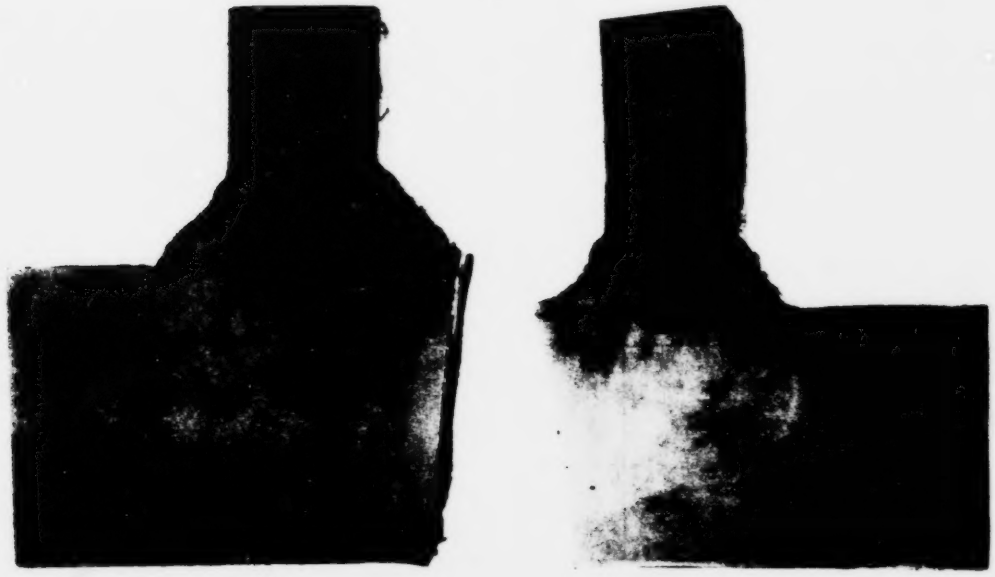


Joint	T	t	ℓ	L	A
52/52-45°	52	52	26-32	442	406
52/26-45°	52	26	14-16	442	406
52/26-AWS	52	26	15-17	442	406

Fig. 1 - Geometry, dimensions, and ACPD probe locations for tested plate T-joints.

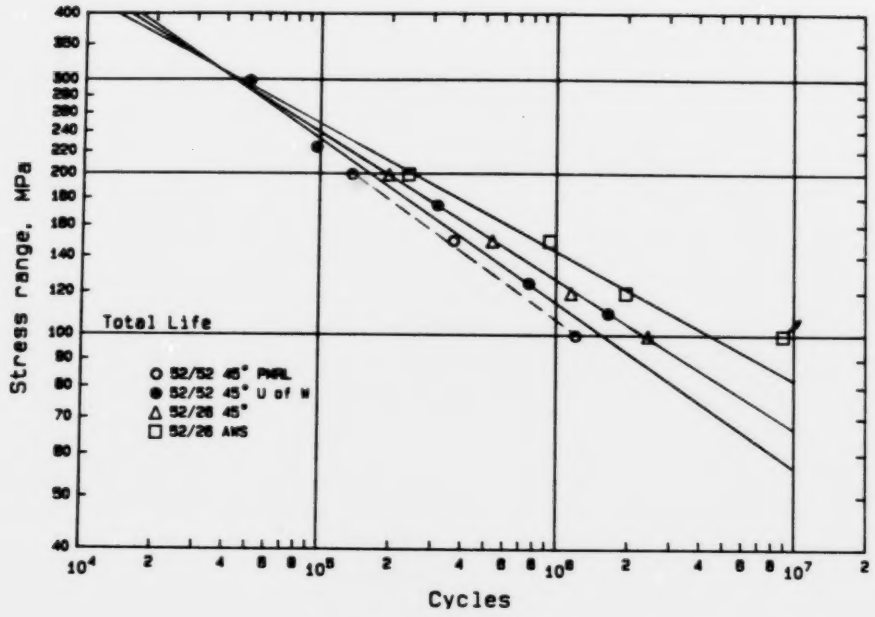


a)

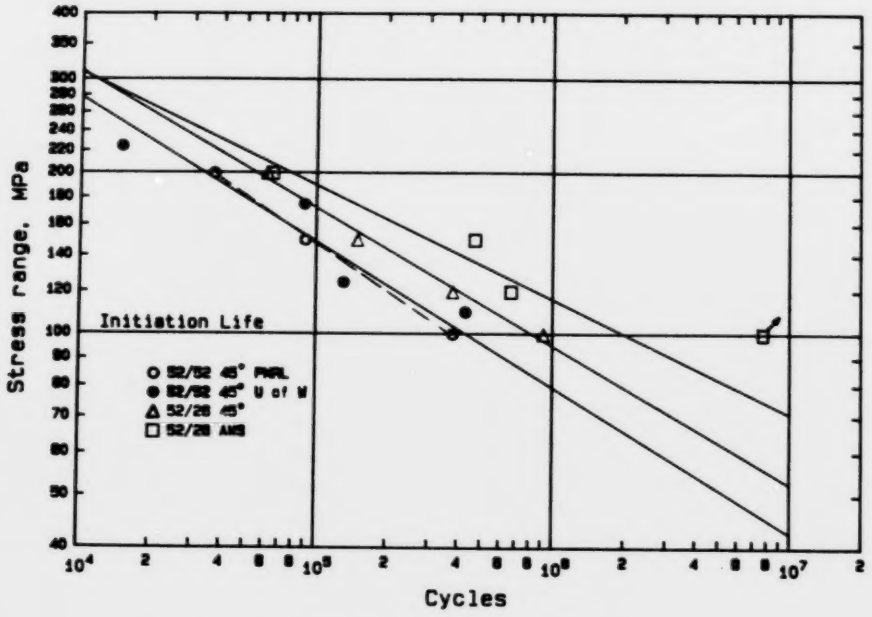


b) c)

Fig. 2 - a) AWS D1.1-86 specifications for improved (concave) weld profile.
b) Cross-section of fractured 52/26 joint with 45° weld profile.
c) Cross section of fractured 52/26 joint with AWS improved weld profile.

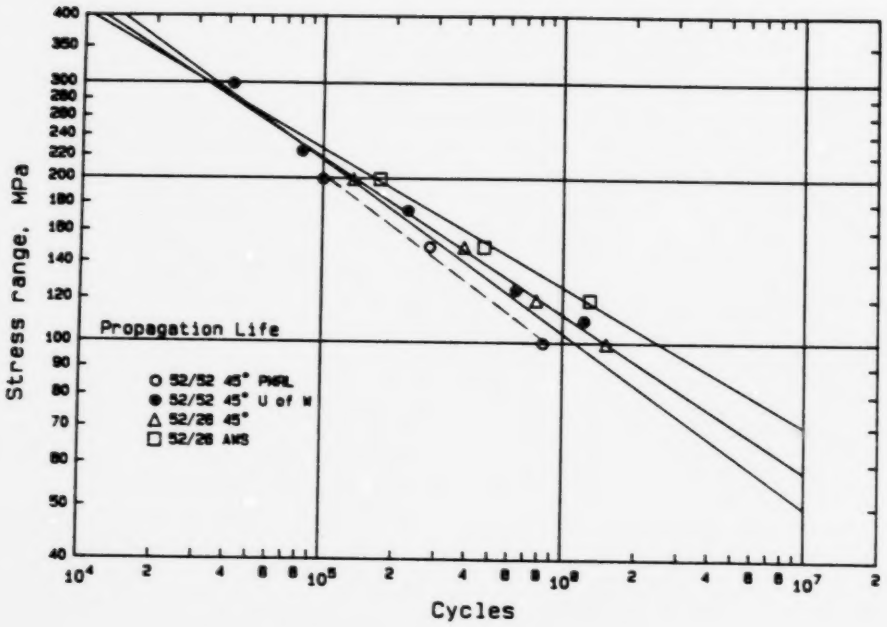


a) Total lives



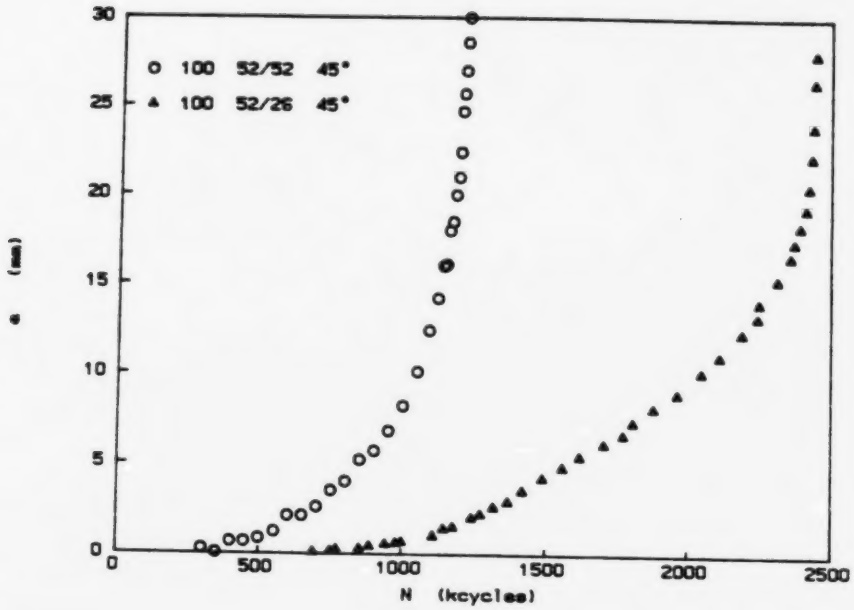
b) Crack initiation lives

Fig. 3. cont'd.

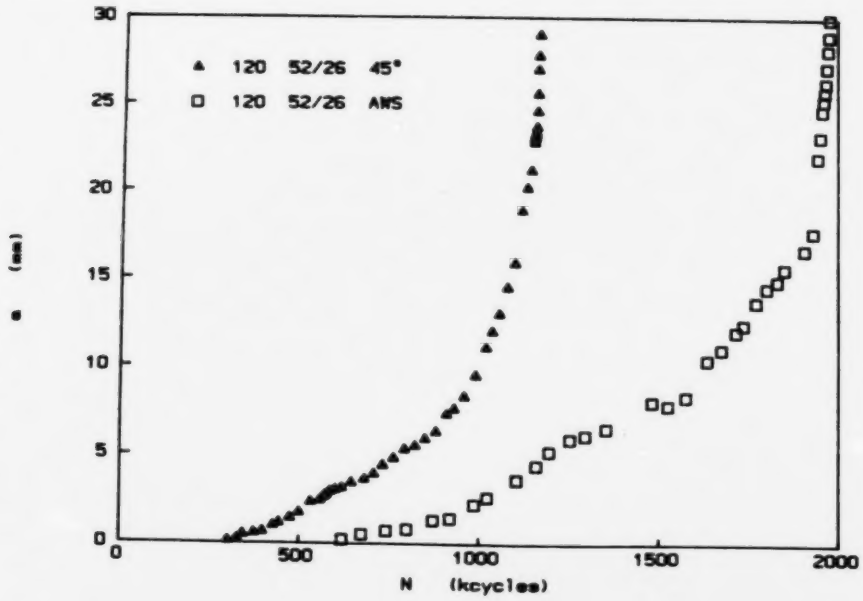


c) Crack propagation lives

Fig. 3 - S-N curves for 52/52-45° full size joints, 52/26-45° joints with thinner attachments, and 52/26 joints with AWS improved weld profile:

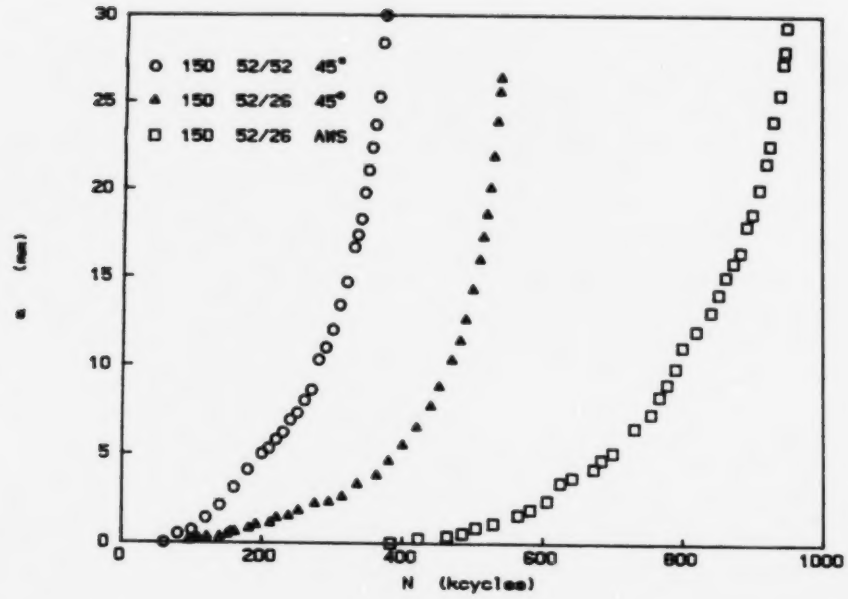


a) 100 MPa

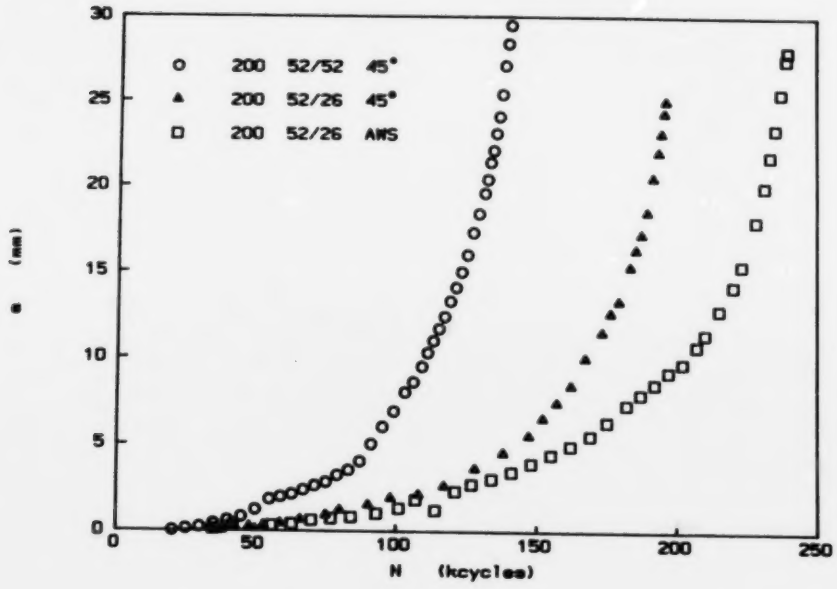


b) 120 MPa

Fig. 4. cont'd.

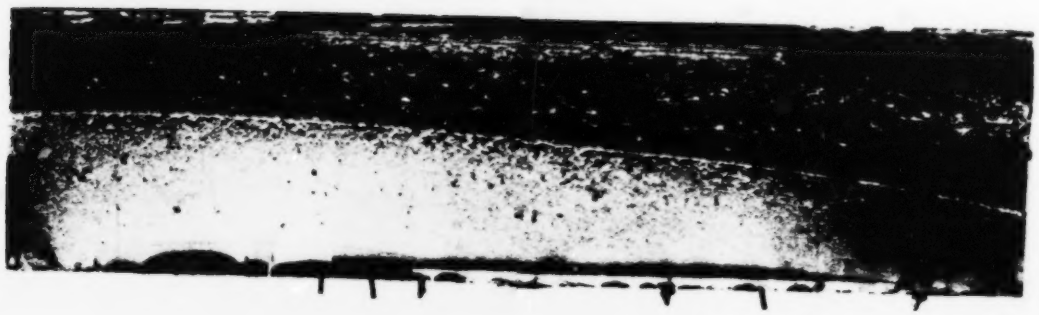


c) 150 MPa



d) 200 MPa

Fig. 4 - Crack growth in 52/52-45°,52/26-45°,and 52/26-AWS joints at stress ranges:

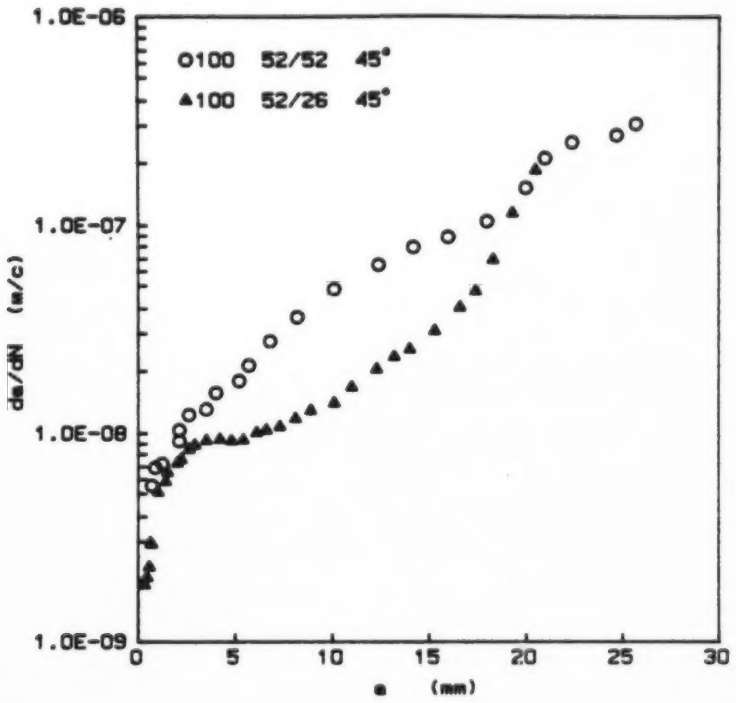


a) 52/52-45°

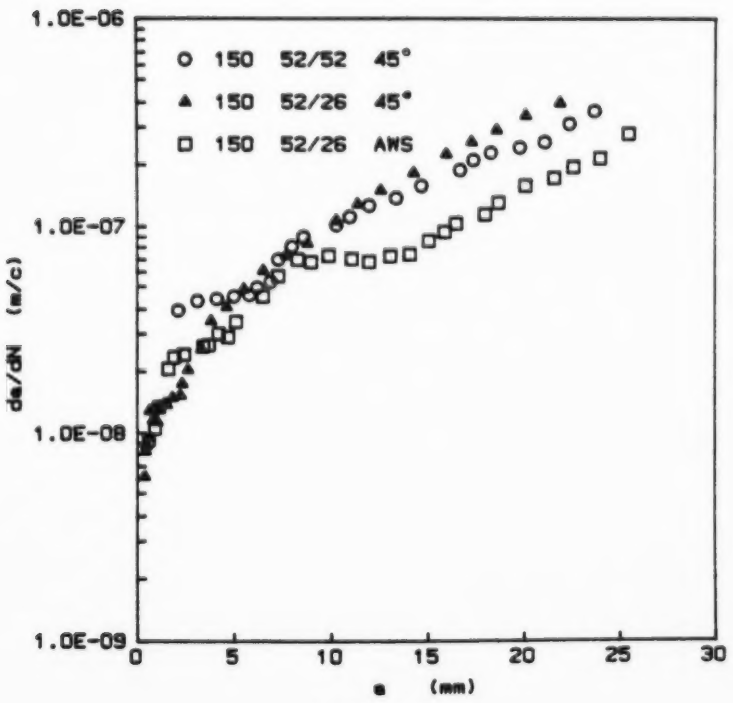
b) 52/26-45°

c) 52/26-AWS

Fig. 5 - Crack development, indicated by beachmarks, in joints tested at 150 MPa stress range:

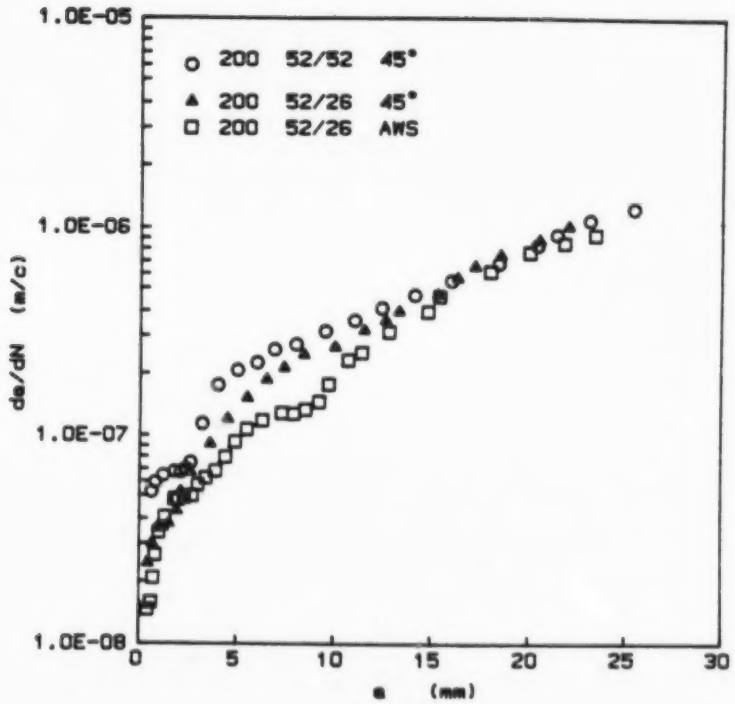


a) 100 MPa



b) 150 MPa

Fig. 6. cont'd.



c) 200 MPa

Fig. 6 - Crack growth rate variation with depth a in 52/52-45°,52/26-45°, and 52/26-AWS joints at stress ranges:

FIGURES AND NEGATIVE NUMBERS

FIGURES	NEGATIVES
1	
2(a)	18214
(b)	16209
(c)	16210
3(a)	18168
(b)	18169
(c)	18170
4(a)	18171
(b)	18172
(c)	18173
(d)	18174
5(a)	11310
(b)	15502
(c)	
6(a)	18246
(b)	18247
(c)	18248